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Power transmission in direct current. Future expectations for Colombia

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ABSTRACT

DC transmission is important when there are problems of instability in AC systems, i.e. when energy is transported through long distance. This issue requires research centers and multinational companies' investments to solve it. One solution is the high voltage DC transmission or HVDC (high voltage direct current). Worldwide HVDC interconnections have helped to solve problems of instability and moreover to easily interconnect systems where voltage and frequency are not compatible. According to that, the aim of this paper is first to analyze the advantages and disadvantages of DC systems compared to AC systems, and then to show future trends in DC systems, as well as present the possible interaction with renewable energies and the convenience of considering the implementation of that technology in Colombia.

Contents

1. Introduction

Globalization process is requesting economic and technological actions to invigorate the trade of energy. As a consequence of this, different strategies of transmission and distribution have emerged in order to achieve cheaper and more efficient interconnection systems.

In this way, technologies and emerging developments such as the power transmission through high voltage direct current, HVDC, have comparative advantages in several aspects in relation to conventional technologies of transmission and interconnection in AC [1,2]. Some of the most common benefits are easy interconnection with regions that have incompatible frequencies, different and flexible control strategies and operating modes, as well as lower costs and better returns when transmitting through very large distances or when there are geographic obstacles such as seas or oceans [1–4].

Therefore, the power transmission through high voltage direct current will become a possibility economically feasible and its commercial and social applications may cover a wide range of possibilities [1]. These facts have been presented since its first commercial application in 1954, in Sweden (Gotland link) by ASEA (an ABB company). Today there are about 100 projects all over the world. They have been working on improving its technology, primarily in the development and progress of semiconductor devices, on converter topologies, and on control strategies to transform HVDC systems in an advantageous element for both trade and transmission of power [5].

On the other hand, renewable energy is assuming a greater importance in the global market. In many cases, the renewable electricity generation centers are far from the consumption points,

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so it is necessary to find solutions to cover long distances, carrying large amounts of energy with minimal losses. Currently, several projects using HVDC technologies in combination with renewable energy are being developed. This is especially true in the case of wind generation systems in marine environments where it is necessary to lay submarine cables [6–9]. An example of this is the case of Borkum 2, in Germany [10], which is offshore wind farm cluster that will be connected to the grid by 400 MW HVDC Light® transmission systems. Full grid code compliance of more than 200 km long HVDC (high voltage direct current) transmission ensures a robust transmission network connection.

Today in Colombia, the Expansion Plan 2004–2018 of UPME plans an electrical interconnection between Colombia and Panama with huge possibilities of using HVDC interconnection. For this reason, research is required in all stages related to the DC transmission process, in order to assess the implications of implementing such technologies in the country.

This paper is divided as follows: first, HVDC systems are discussed, with emphasis on the comparison with HVAC systems, types of HVDC links and the types of converters employed. Then, the current state of HVDC systems in Colombia is presented, as well as the impact and possible trend of future development of HVDC systems. Finally, conclusions will be presented.

2. HVDC systems

The continued growth in electricity demand requires ongoing expansion plans to increase transport capacity, and promote the interconnection of regions that sometimes are separated by great distances. The need to transmit energy across the sea is very common as well as to interconnect asynchronous systems of different frequencies. This implies finding technically and economically feasible systems that ensure stability and proper exchange of energy.

As it is known, the power transfer in AC lines depends on the angular difference between voltage phasors at both ends of the line. For a level of power transfer given these angles, it increases accordingly to the distance. But at the same time, it decreases the stability of systems where the interconnections are particularly long. The power transmission using submarine cables is limited to short distances in the case of HVAC due to high dielectric capacity cables, and compensating inductors are required to use every 15–20 km parallel, limiting the effective transmission distance [11]. In AC systems with different frequencies, it is impossible to interconnect them directly.

The foregoing limitations have been forced to seek alternative solutions, which with technological developments and advances in power electronics have enabled progress in the power transmission. Some examples of these advances are: developments in phase controllers implemented with thyristors, flexible AC transmission systems (FACTS) and high voltage direct current transmission (HVDC) [12].

Before analyzing the advantages and disadvantages of DC systems compared to AC systems, a summary will be done and there will be a chronological brief presentation of DC systems development.

In the AC system interconnections through DC links, converters AC/DC/AC are required. The implementation of converters requires power electronic components such as diodes, thyristors and transistors. The first mercury vapor rectifier and the first experiments with mercury thyratrons and valves were made before 1940. The first commercial HVDC transmission was carried out in Sweden in 1954, and the first solid state valve HVDC was built in 1970. The first developed converters were built with mercury valves, and later with thyristor valves or SCR (Silicon Rectifier Controller), which were implemented with characteristics of controlled current source (CSC). Powered CSC HVDC links are more powerful and longer. For example, the one from Itaipu, Brazil, that was built in 1984 [13], has one of the highest voltages HVDC transmission (±600 kV). With the advent of power self-commuted elements, such as OFF by gate thyristors (GTO – Gate Turn-Off Thyristor) and insulated gate transistors (IGBT – Insulated Gate Bipolar Transistor), converters with characteristics of controlled voltage source (i.e. VSC) have been developed. They have the particularity of not changing the polarity of the lines when changing the direction of power flow, as it does under the CSC.

Due to the constant evolution of power transmission systems, it is now very common to find the term HVDC Light® [14]. HVDC Light® is the successful and environmentally friendly way to design a power transmission system for a submarine cable, an underground cable or network interconnection. HVDC Light® is HVDC technology based on voltage source converters (VSCs). With extruded DC cables, power ratings from a few tens of megawatts up to several hundreds of megawatts are available. This technology is able to rapidly control both active and reactive power independently from each other and to keep stable voltage and frequency. This gives total flexibility regarding to the location of the converters in the AC system since the requirements of short-circuit capacity of connected AC networks is low (SCR down to zero). Fig. 1 shows the HVDC Light® scheme.

2.1. Comparison between HVAC and HVDC systems

For similar levels of isolation and conductors with the same specifications, it is possible to transmit more power through a bipolar DC link which uses two conductors than using a three-conductors AC link [15].

The electric field at the surface of the conductors is lower in HVDC and the measures to mitigate it are also less demanding [16]. Losses in DC systems with two conductors, with the same current transmission capacity of three AC conductors, are lower (about two thirds, compared to the AC cables), and in long lines, the losses of converters are compensated with smaller losses presented by conductors. So for the same power level the number of DC lines is lower, decreasing the size of the towers, and reducing the right of way significantly [1,15,17]. The electric and magnetic fields generated by HVDC lines are static; they have the same order of magnitude than those generated by the Earth, and, in principle, they do not affect the living beings directly. Due to these factors, the cost of DC lines is smaller, has low visual impact and is more environmentally friendly.

On the other hand, the technical advantages and lower costs of HVDC lines are affected by the high prices of terminal equipment, especially converters and filters.

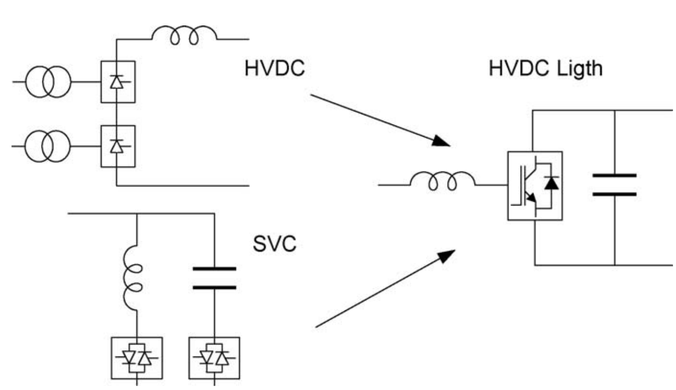

Fig. 1. Scheme of HVSC Light®.

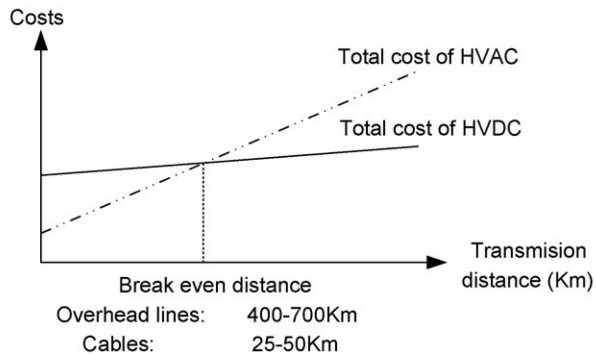

Fig. 2. Costs of AC and DC lines according to distance [17].

In Fig. 2, the variation for comparable peak voltages is shown, as well as the transmission costs for AC and DC lines according to distance. As can be seen, when there are short distances, using AC transmission is the best idea. Nevertheless, for long distances the best solution is the DC transmission. There is one breakpoint between AC and DC overhead lines, which is located between 400 and 700 km for voltage levels and between 55 and 700 kV [17], which allows one to determine the most cost-effective alternative.

In the last paragraphs, it has been presented a comparison between HVAC and HVDC systems, from the point of view of transmission costs. Then a comparison will be made from the technical point of view, which will consider some issues such as angular differences, stability limits, line compensation, problems of AC interconnection, and ground impedance.

As mentioned at the beginning of Section 2, the power transferred in one AC line depends on the angular difference between voltage phasors at the ends of the line, and because the angle increases depending on distance. The line capacity is reduced in long lines. In this way, the power transferred in a DC line is independent of the distance.

In long AC lines, compensators are required to improve stability limits, i.e. to transmit a greater amount of power and control voltage. It is necessary to use inductors, capacitors and static compensators of reactive power, among others. In DC lines, these elements are not necessary because compensation is not required.

The interconnection of two AC systems requires the coordination of the automatic generation controllers from the two systems, using frequency signals and power. However, the action of the controllers may be affected by the presence of power oscillations, which in turn can lead to frequency variations, increased levels of failure and disturbances in the transmission from one system to another. In DC interconnections, some of the variables of AC systems are not as relevant or they do not have the same importance; and prompt action of the control systems substantially reduces the disadvantages mentioned above. For example, it allows the interconnection of asynchronous systems, such as Garabi conversion station [18] and Back-to-Back, installed between 2000 and 2002, which connects two systems with different frequencies: Argentina at 50 Hz and Brazil at 60 Hz.

On the other hand, in AC systems the existence of ground currents gets affected due to the high magnitude of ground impedance, which not only affects the efficiency of transferred power, but also produces interference in telephone grids. In DC systems, the impedance is lower; the ground can be used as a return conductor and produces no interference.

2.2. Types of HVDC links

A HVDC system like the one shown in Fig. 3 is made up of a rectifier station (station 1), a direct current line, and an inverter

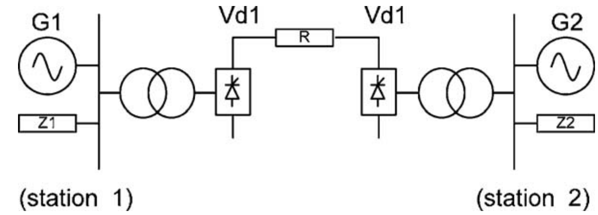

Fig. 3. HVDC system.

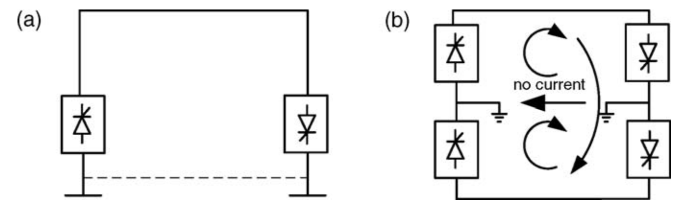

Fig. 4. HVDC link (a) monopolar and (b) bipolar.

station (station 2). The transmitted power P depends on the difference from direct voltages Vd1 and Vd2 present in the converters and in the resistance R from the DC line [19].

The interconnection in a HVDC system can be monopolar as shown in Fig. 4a, with a line and return; or bipolar as shown in Fig. 4b with two lines of different polarities and return.

In some cases, the interconnection can be homopolar, formed by two lines of the same polarity and return. Alternatively the returns can be made by ground, by sea or by metallic media. In some links, negative polarity is preferred because the electric field at the surface of the conductors has, in some ways, less impact with this polarity. For submarine links, it is necessary to use cables using impregnated paper insulation MI (Mass Impregnated), or extruded as the well known XLPE (Cross-Linked Poliethylene) extruded cables. In these cases, due to the fact that the sea water has very low resistivity, 0.3 Ω m (lower than the ground resistivity) the current return is made primarily by water.

In bipolar links, when both poles operate under normal conditions and the currents are equal, no current circulates in the ground return. They also have the advantage that under fault conditions of the two DC lines, they can be used temporarily as a metallic return.

2.3. Types of converters

HVDC systems require electronic converters to convert AC to DC power or vice versa. There are essentially two types of configurations of three-phase converters for this conversion process [20]: current source converter, CSC (Fig. 5) and voltage source converter, VSC (Fig. 6)

During the period between the 1950 and 1990 HVDC systems used only CSC topologies. Traditional CSC used mercury arc valves until the early 1970, after this decade thyristor valves were used as core of switching devices.

From the 1990, the alternative of the VSC became economically viable due to the availability of new power electronic self commutated devices (GTO's and IGBT's) and greater computing capacity by programmable devices.

HVDC transmission systems can use CSC's current or VSC's depending on economic, environmental and technical development required for a particular project. Below are presented in Table 1, a comparison between these two types of converters [16]:

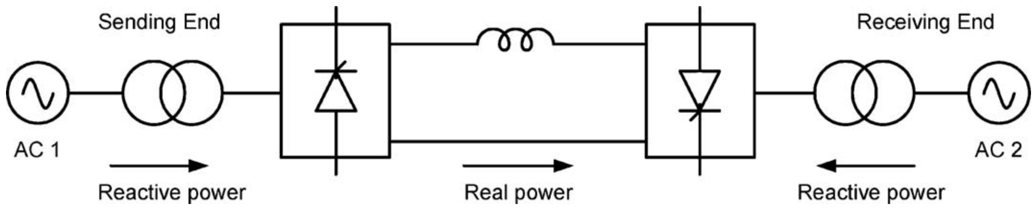

Fig. 5. HVDC system based on CSC technology with thyristors.

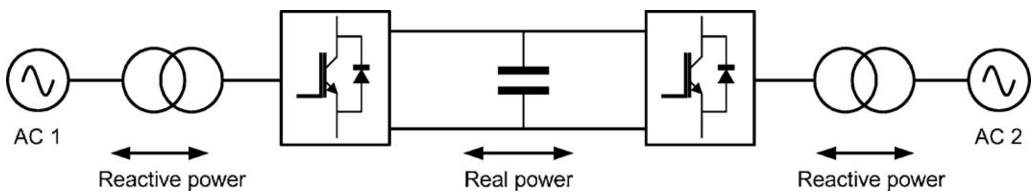

Fig. 6. HVDC system based on VSC technology built with IGBTs.

3. Actual condition of HVDC systems in Colombia

The initiative to explore the implementation of HVDC systems in Colombia comes from the need to interconnect and transport electric power between the countries of the region. For this reason, in 1991, an agreement called TRACTEBEL (“Proyecto de los tres”) was posed for Colombia, Panama and Venezuela. By 1996 OLADE had realized different energy analysis for the purpose of enabling such connection. In 2001 ISA and ETESA agreed to conduct the feasibility study of such interconnection (energetic, economic and environmental analysis) [21]. In 2003, the governments of Colombia and Panama met in the “X Reunión de Vecindad Colombo-Panameña” (April 28, Cartagena de Indias) and decided to promote the project through the signature the “Memorando de entendimiento”. In 2004, the “Unidad de Planeación Minero Energética, UPME”, within the “Plan de Expansión Preliminar 2004–2018” [22], presents several preliminary analysis about the interconnection between Colombia and Panama based on the feasibility study presented by ISA and ETESA in 2003. In this study there are three alternatives for interconnection between Colombia and Panama.

The first alternative is a 230 kV AC line with double circuit from the Cerromatoso substation in Colombia to 230 kV and Panama II substation to 230 kV with an approximate length of 434 km. Due to the length of the interconnection, it is necessary to review the appropriateness of placing an intermediate substation halfway to manage voltage by shunt compensation. Approximate cost is 173 MUS$, but it has instability by disturbance.

A second alternative is the connection between the Cerromatoso substation and Panama II via HVDC monopolar link at 250 kV, with a length of 514 km. Fig. 7 shows this alternative route. The submarine section would be approximately 51-km long and land stretches will have the remaining length of DC line.

The third alternative is an aerial HVDC monopolar 250 kV line, with land route between the Cerromatoso and Panama II substations, 571 km. Fig. 8 shows the proposed route of this alternative.

It was concluded after the study provided by ISA that the interconnection between both countries through AC lines would not be desirable from the electrical standpoint because of its unstable behaviour. HVDC interconnection is technically feasible as its electrical performance is adequate to satisfy the quality, safety and reliability criteria.

In 2007, ISA and ETESA consisted of the bi-national company Interconexión Eléctrica Colombia Panamá S.A. – ICP-. In 2008, the governments of Colombia and Panama signed an intention memorandum, motivated by an interest in strengthening a bilateral electrical interconnection scheme that will benefit the progress and development of the countries. In 2009, the governments of Colombia and Panama signed an agreement to set up, together, the operational and commercial framework that would facilitate the electricity exchange between the two countries.

Table 1
Types of converters.

	Types of converters	
	CSC	VSC
AC side	Acts as a constant voltage source	Acts as a constant current source
	Requires a capacitor as its energy storing device	Requires an inductor as its energy storing device
	Requires large AC filters for harmonic elimination	Requires only a small AC filter for higher harmonics elimination
	Requires reactive power supply for power factor correction	Reactive power supply is not required as converter can operate in any quadrant
DC side	Acts as a constant current source	Acts as a constant voltage source
	Requires an inductor as its energy storing device	Requires a capacitor as its energy storing device
	Requires DC filters	Energy storage capacitor provides DC filtering capability at no extra cost
	Provides inherent fault current limiting features	Problematic for DC line faults since the charged capacitor will discharge into the fault
Switches	Line commutated or force commutated with a series capacitor	Self commutated
	Switching occurs at line frequency	Switching occurs at high frequency
	Lower switching losses	Higher switching losses
Rating range	0–550 MW per converter	0–200 MW per converter
	Untill 600 kV	Untill 100 kV

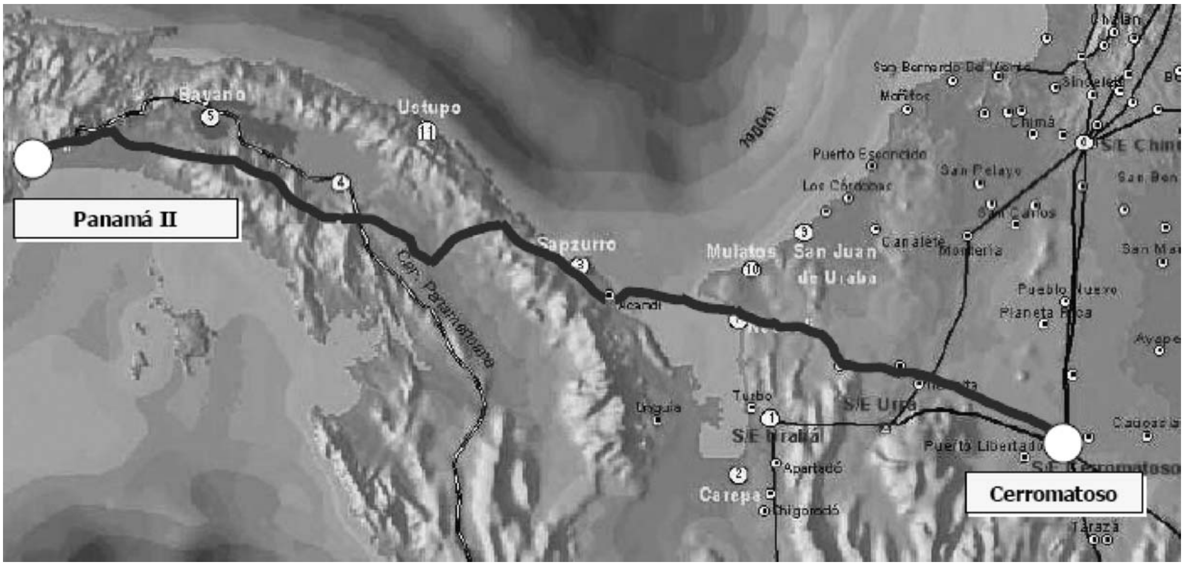

Fig. 7. 2nd Alternative. HVDC link.Source: ISA.

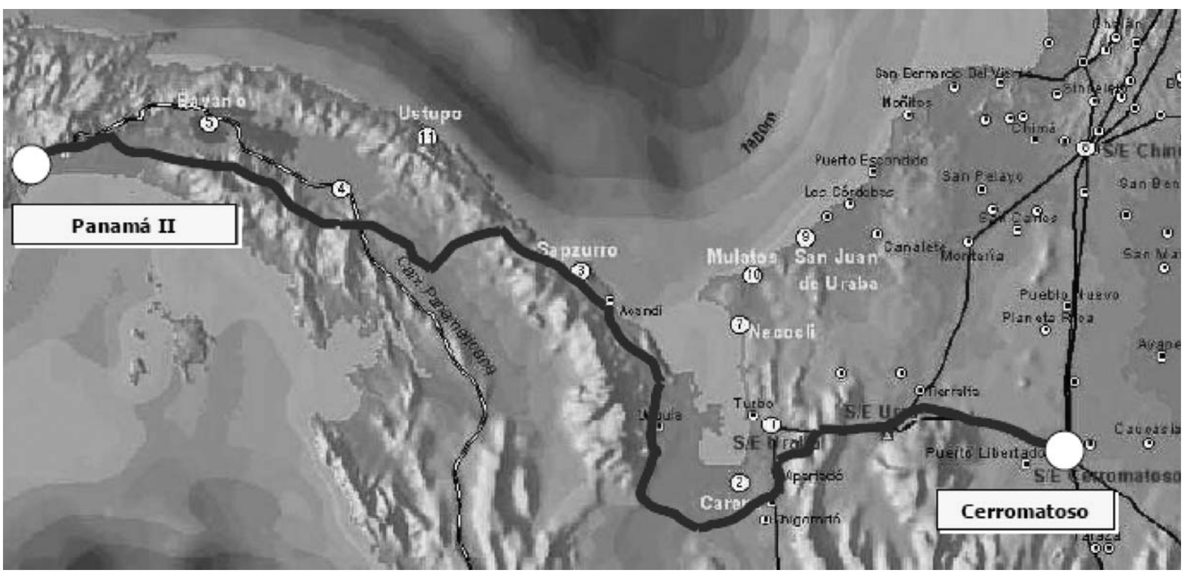

Fig. 8. 3rd Alternative II. HVDC link (Source: ISA).

Currently, the company Interconexión Eléctrica Colombia Panamá S.A. – ICP- has set a work schedule [23], which plans to end the dealing R + D part in September 2010, to carry out the construction phase between October 2010 and the end of 2013, which means that in 2014, the link would be operational.

Finally, the system features to implement are: HVDC system with a maximum link capacity of 300 MW (with possible extension to 600 MW in the second phase). The line route is mixed (aerial and maritime), with an approximate length of 614 km, of which 340 km correspond to Colombia and 274 km to Panama. The undersea section is 55 km, which means environmental and social benefits for both countries.

4. Impact and possible trend of future development of HVDC systems

To analyze and consider the impact of DC systems, it should be noted that, currently, the HVDC systems are used in power transmission in long and short distances, with Back-to-Back stations (AC/DC/AC conversion without transmission line), to interconnect different frequencies systems or to ensure the stability of large power systems. Moreover, at present, the HVDC development is aiming to build power electronic devices in silicon

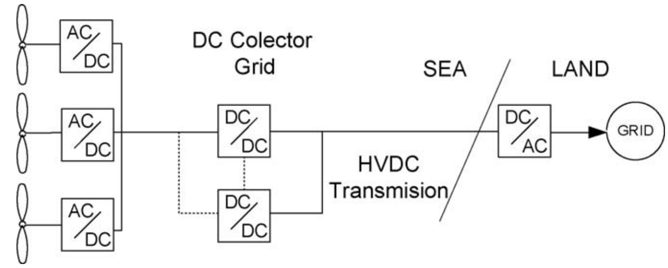

Fig. 9. Offshore wind farms connected to the main grid over medium and high voltage DC converters.

Table 2
HVDC Light® projects.

Project	In service	Power MW	DC voltage (kV)	Transmission distance	Application
HÄLLSJÖN, Sweden	1997	3	±10	10 km (over-head)	Pilot system
GOTLAND, Sweden	1999	50	±80	70 km	Wind, undergrounding
DIRECTLINK, Australia	2000	3 × 60	±80	65 km	Undergrounding
TJÆREBORG, Denmark	2000	7,2	±9	4,4 km	Wind, undergrounding
EAGLE PASS, USA	2000	36	±15.9	NA (back-to-back)	Grid reliability
CROSS SOUND, USA	2002	330	±150	40 km	Grid reliability
MURRAYLINK, Australia	2002	220	±150	180 km	Undergrounding
TROLL A, Norway	2005	2 × 41	±60	67 km	Offshore
ESTLINK, Estonia, Finland	2006	350	±150	105 km	Grid reliability, undergrounding
VALHALL, Norway	2009	78	150	292 km	Offshore
Borkum 2, Germany	2009	400	±150	203 km	Wind

Source: www.abb.com/hvdc.

carbide [2], which has the property of holding up high voltage and temperature, using much thinner wafers than conventional ones made of silicon. The new devices allow the converters to be constructed with better features and lower cost. Additionally, the technological improvements in extruded cables have contributed to make them cheaper than impregnated paper cables. Thus a trend to lower costs for the HVDC systems implementation can be deduced.

Taking into account that VSC converters always maintain the same polarity, they can be connected in parallel to form branches similar to the AC topology. In the near future it will allow not only DC transmission but also DC distribution to be used in new ways to convert DC/DC. This would allow the changing of the voltage levels, to meet the purposes and needs of the distribution, in ranks near the 30 kV DC which will provide levels at which the conversion DC/AC will be allowed to continue with the conventional 13.2 kV AC distribution.

In a not too distant future, when competitive electronic transformers and limiters current devices are developed, which convert the range of medium and low voltage DC, it will be possible to have DC distribution networks with the advantage of carrying more energy than conventional systems and meet demand better, for example in congested sites of large cities with little place for installation of new wires [24–28]. The transition to low DC voltage will take longer because the installed domestic and industrial equipments work mainly with AC power.

Additionally, the development and increment of the electric generation from renewable sources (solar farm, wind farms, small gas-fired and hydroelectric) should be considered as it is respectful of the environment and the DC transport and energy recollection is easier because it does not depend on frequency. Moreover one limitation of renewable sources of energy is that they are often best captured in places far from where energy is used: remote bays with large tides, desert areas with bright and constant sun, and windswept ridges. In these cases, losses associated with transmitting the power over standard alternating current (AC) power lines can lead to very significant losses. This is where high voltage direct current (HVDC) transmission lines come in. With the actually HVDC technology, energy losses can be kept to about 3% per 1000 km. This makes the connection of remote generating centers much more feasible. An example of the renewable energy in conjunction with HVDC systems use is the Tjaereborg project in Denmark for wind generation proposed by the Danish Ministry of Energy, National Forest, The Agency of Nature and the power industry to be developed before 2015. Another example is the project based on wind power with HVDC transmission in Jeju Island, Korea [29]. Fig. 9 presents a possible configuration scheme of offshore wind farms connected to the network [30].

In the Table 2 are presented several projects working HVDC Light®.

5. Conclusions

This paper has exposed the main features of HVDC systems. It has made a comparison with HVAC systems and shown that HVDC systems have good characteristics (electrical, economic and environmental) when transmitting large amounts of energy over long distances. It has also described the main configurations and basic topologies for the implementing of such systems (CSC and VSC).

Besides, it has mentioned the importance for Colombia to implement this technology for long interconnections. In the same way it has viewed the ability to use HVDC as an alternative distribution and expansion to solve the increase in demand in large cities where little space is available, and to interconnect isolated and remote areas which do not have a good electric service in conjunction with renewable energy sources.

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